

This paper was presented by Jeff Dale at the Battelle Conference  
entitled, "Remediation of Chlorinated and Recalcitrant Compounds;  
Proceedings of the Third International Conference," held in Monterey,  
CA, May 20-23, 2002

## COMPARISON OF DIALYSIS MEMBRANE DIFFUSION SAMPLERS AND TWO PURGING METHODS IN BEDROCK WELLS

*Thomas E. Imbrigiotta* (timbrig@usgs.gov), Theodore A. Ehlke, Pierre J. Lacombe  
(U.S. Geological Survey, West Trenton, New Jersey)  
Jeffrey M. Dale  
(U.S. Navy, Lester, Pennsylvania)

**ABSTRACT:** Collection of ground-water samples from bedrock wells using low-flow purging techniques is problematic because of the random spacing, variable hydraulic conductivity, and variable contamination of contributing fractures in each well's open interval. To test alternatives to this purging method, a field comparison of three ground-water-sampling techniques was conducted on wells in fractured bedrock at a site contaminated primarily with volatile organic compounds. Constituent concentrations in samples collected with a diffusion sampler constructed from dialysis membrane material were compared to those in samples collected from the same wells with a standard low-flow purging technique and a hybrid (high-flow/low-flow) purging technique. Concentrations of trichloroethene, cis-1,2-dichloroethene, vinyl chloride, calcium, chloride, and alkalinity agreed well among samples collected with all three techniques in 9 of the 10 wells tested. Iron concentrations varied more than those of the other parameters, but their pattern of variation was not consistent. Overall, the results of nonparametric analysis of variance testing on the nine wells sampled twice showed no statistically significant difference at the 95-percent confidence level among the concentrations of volatile organic compounds or inorganic constituents recovered by use of any of the three sampling techniques.

### INTRODUCTION

Wells in fractured bedrock historically have been sampled by first purging at least three casing volumes of water from the well at relatively high flow rates. The advantage of this technique is that the sample collected is a composite of the ground water from all fractures that intersect the open interval of the well. The disadvantages of high-flow purging are the production of a large amount of purge water, which may need to be treated if it is contaminated, and the potential increase in turbidity of the water, which may require filtration to avoid collecting samples with artificially high concentrations of inorganic constituents. To counteract these disadvantages, it has been suggested that a low-flow purging technique might be used in wells in fractured bedrock as it is in wells screened in unconsolidated aquifers (N.J. Department of Environmental Protection, 1992; Giles and Story, 1997). Low-flow purging certainly produces less purge water and tends to minimize the turbidity caused by pumping (Puls and Barcelona, 1996); however, a major potential problem with the use of low-flow purging in fractured-rock wells is that the intake of the pump is set arbitrarily at the mid-depth of the open interval, which may not correspond to the depth of the main fracture contributing flow and contaminants to the well. The open intervals of fractured-rock wells must be geophysically logged or samples must be collected at multiple depths initially to determine the appropriate depth for low-flow purging. Also, low-flow purging requires monitoring field parameters to

stability, which may be a time-consuming process at low flow rates. Additionally, both low-flow and high-flow purging methods require that pumps and/or discharge lines be decontaminated or replaced between wells.

A more recently developed sampling method that avoids some of the problems encountered with purging techniques is the use of diffusion samplers. Diffusion samplers are semi-permeable membranes filled with deionized water that are hung in a well at a specified depth. The principle of the diffusion sampler is that, given enough time, the water chemistry on the outside of the membrane (in the well/open interval) will equilibrate with the water chemistry on the inside of the membrane. After equilibration has occurred, the diffusion sampler is retrieved and the contents are sampled. With this technique, no purge water is produced for treatment, the diffusion samplers can be constructed of disposable materials so that no decontamination is needed between wells, and filtration of the water samples is unnecessary because no particulates can enter the sampler. Most of the work on diffusion samplers to date has been done using low-density polyethylene membranes to sample for volatile organic compounds (VOCs) (Vroblesky, 2001a; Vroblesky, 2001b). Other membranes, such as regenerated-cellulose dialysis membrane, need to be tested to determine whether diffusion samplers may be useful in sampling for inorganic water-quality constituents in addition to VOCs.

The objective of this paper is to present the results of a study comparing the ability of three sampling techniques-sampling with a regenerated-cellulose dialysis membrane diffusion sampler, a low-flow purging method, and a hybrid high-flow/low-flow purging method to recover both VOCs and a selected number of inorganic constituents (both cations and anions) from a set of wells in fractured bedrock. The comparisons were done by sampling the wells using the three sampling techniques in sequence. The comparisons were repeated and the data were analyzed graphically and statistically to determine whether differences in the recovery of water-quality constituents among the three sampling techniques were significant.

**Study Site.** The wells sampled in this study were installed in two bedrock units of the Newark Basin: the Lockatong Formation, which consists primarily of shales, mudstones, and siltstones, and the Stockton Formation, which consists primarily of sandstones (Lacombe, 2000). The formations that underlie the study site consist of a series of bedding units that dip to the northwest. The primary water-bearing fractures are the bedding-plane partings that are arranged along the strike of the formations. Most of the ground-water flow occurs along strike, from the northeast to the southwest (Lacombe, 2000).

The wells sampled are on or near a former Naval facility in West Trenton, New Jersey, where jet engines were tested. Trichloroethene (TCE) was used as the heat-transfer medium in a 25,000-gallon-capacity refrigeration system. Several leaks and spills over a 40-year period introduced a sizeable amount of TCE to the fractured-bedrock aquifer (International Technology Corporation, 1994). TCE concentrations at the site range from less than 1 µg/L (microgram per liter) to as much as 160,000 µg/L. Cis-1,2-dichloroethene (cisDCE) and vinyl chloride (VC) also have been found in high concentrations, indicating that anaerobic biodegradation of TCE is occurring in several areas of the ground-water system beneath the site.

## **MATERIALS AND METHODS**

Ten wells were selected for inclusion in this study on the basis of their known range of TCE concentrations, past pumping history, and accessibility. Each well had a single open interval between 3.0 and 7.6 m (meters) (10 to 25 ft (feet)) long and each was geophysically logged prior to the start of the experiment. Caliper logs, temperature logs, and resistivity logs were run and helped identify the presence of one to four fractures in the open interval of each well. The depth of the largest fracture, determined from the results of this geophysical work, was used as the initial diffusion-sampler and low-flow-purging depth in each well.

The diffusion samplers were constructed of regenerated cellulose tubular dialysis membrane. The dialysis membrane has a molecular weight cutoff range of 6,000 to 8,000 Daltons and a nominal pore size of approximately 0.002  $\mu\text{m}$  (microns). The membrane has a lay-flat width of 100 mm (millimeters) and a filled diameter of 63.7 mm. The volume of the dialysis membrane when filled with 0.2  $\mu\text{m}$  filtered deionized water was 31.8 mL/cm (milliliters per centimeter). The length of the dialysis membrane diffusion samplers ranged from 0.9 to 1.4 m (3.0 to 4.7 ft) depending on the volume of water needed for sampling. The dialysis membrane was cleaned according to the manufacturer's specifications to remove residual trace metals and sulfides prior to construction (Dan Keil, Membrane Filtration Products, Inc., written communication, January 2001).

Low-density polyethylene diffusion samplers also were used in this work, but the results obtained using this type of sampler were not compared to the results obtained with other sampling techniques. Polyethylene diffusion samplers were used only to measure the depth in the open intervals of the wells at which the concentration of VOCs was highest. These samplers were constructed of 2-mil-thick polyethylene and had a volume of 200 mL.

The field experiment was conducted on 9 wells in March 2000 and on 10 wells in March 2001. The experiment consisted of sampling each of the selected wells at the site in the following order: First, the dialysis membrane diffusion sampler was lowered to the depth of the chosen fracture and allowed to equilibrate for 7 days. After this period of equilibration, the sampler was retrieved and immediately drained into appropriate sample containers through the stopcock installed at one end. Next, an electrically powered stainless-steel submersible pump was lowered to the same depth at which the diffusion sampler had been suspended. Low-flow purging was done at approximately 0.5 L/min (liters per minute) until monitored field parameters (temperature, pH, specific conductance, dissolved-oxygen concentration, redox potential, and turbidity) stabilized, after which water samples were collected from the discharge line. Last, for the hybrid sampling, the same submersible pump was raised up into the casing to a depth at least 1.5 m (5 ft) above the open interval. One and one-half casing volumes were then flushed out at 3.8 to 11.4 L/min (1 to 3 gal/min (gallons per minute)) (high purge rate). Next, the flow rate was reduced to 0.5 L/min (low purge rate) and field parameters were monitored to stability. Once stability was attained, samples were collected from the discharge line. Samples were analyzed for VOCs and selected inorganic parameters including calcium, iron, chloride, and alkalinity according to standard analytical methods (U.S. Environmental Protection Agency, 1990). Graphical and statistical comparisons were conducted to determine whether results obtained by using the three sampling techniques

differed for any of the parameters investigated. A nonparametric analysis of variance on ranks was done for each water-quality parameter to determine the overall significance of the difference among sampling techniques (SAS Institute Inc., 1989). The results were ranked for each well each time it was sampled by giving the sampling technique that resulted in the lowest recovery a value of 1, the technique that resulted in the highest recovery a value of 3, and the technique that resulted in the intermediate recovery a value of 2.

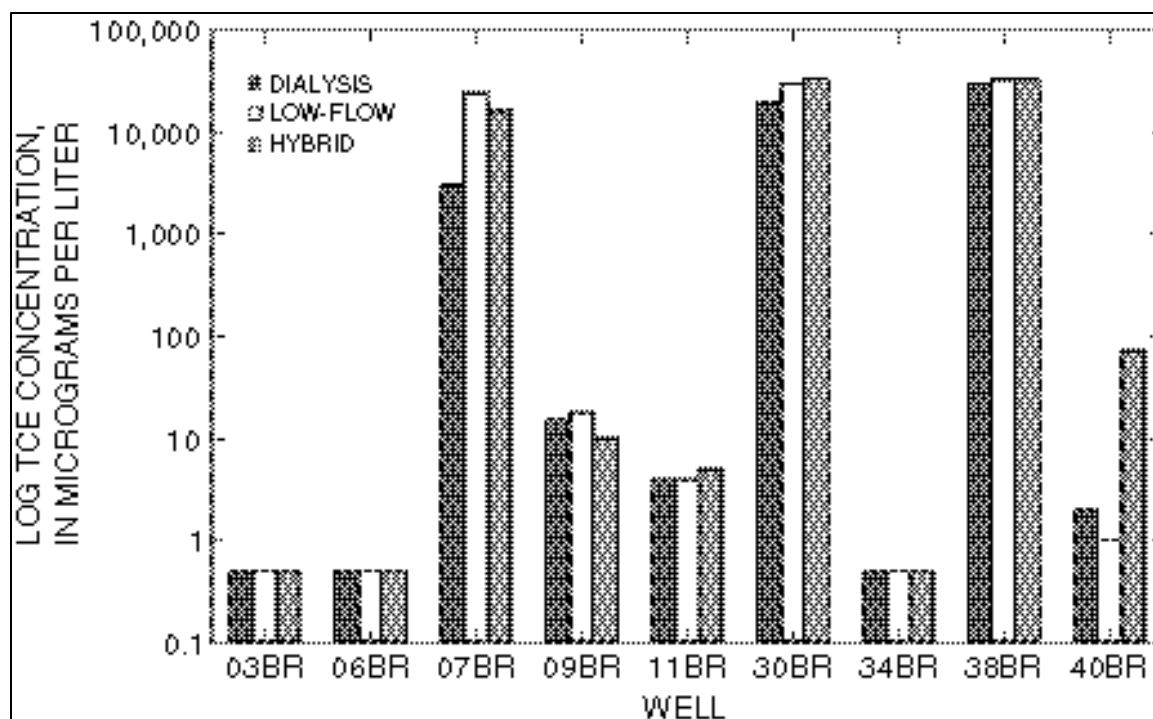
## RESULTS AND DISCUSSION

**Volatile Organic Compounds.** Comparison of the TCE concentrations in the March 2000 samples indicated that there was generally good agreement among results for samples collected using dialysis membrane diffusion samplers, low-flow purging, and hybrid purging in 7 of 9 wells (Table 1 and Figure 1). The results for cisDCE and VC were similar to those obtained for TCE. For well 07BR, the TCE concentrations recovered with the diffusion sampler were nearly an order of magnitude smaller than those recovered by using both the low-flow and hybrid purging techniques. For well 40BR, both the diffusion-sampler and the low-flow-purging results were an order of magnitude smaller than the hybrid-purging results. The reason for the differences in results between these two wells and between these wells and the other seven wells is not immediately apparent, because all wells were sampled in an identical fashion. One possible explanation is that the diffusion sampler and low-flow purging pump intake were positioned at a depth that differed from the depth of the primary fracture contributing TCE-contaminated water to the open interval in each of these two wells.

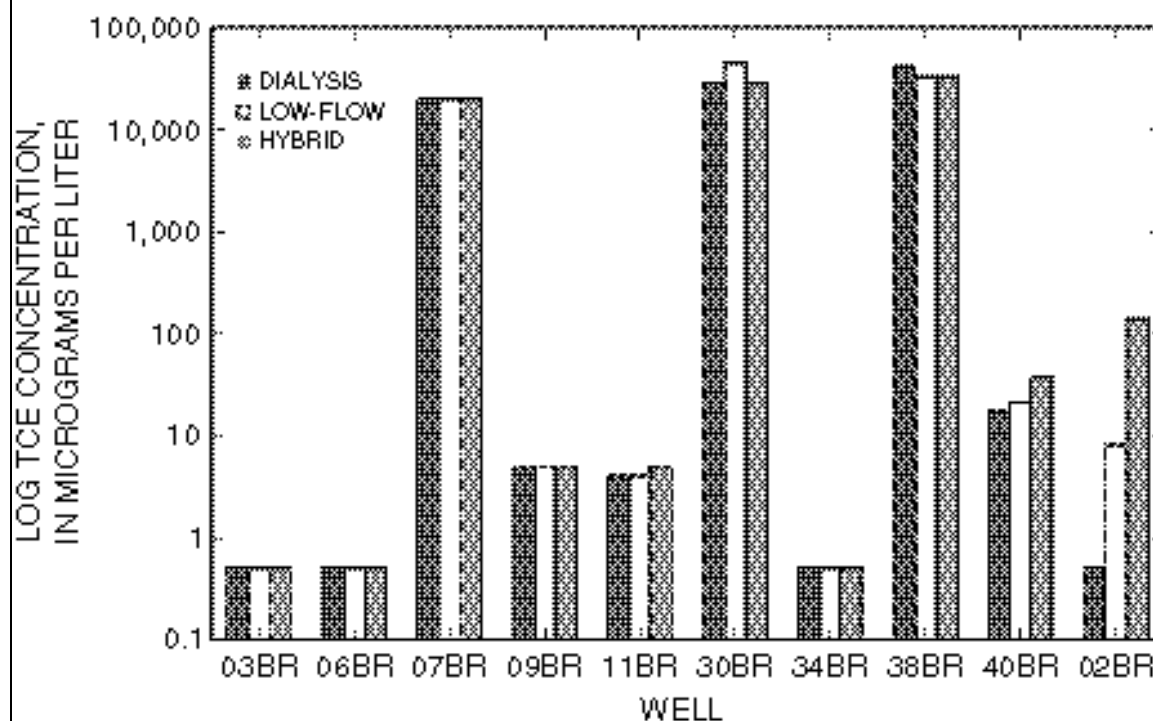
To determine more accurately where most of the VOC-contaminated water was entering the open intervals of these wells, multiple small-volume polyethylene diffusion samplers were hung at 2-ft intervals in the open intervals of the wells. After equilibration, samples from these diffusion samplers were analyzed for VOCs only. The depths at which the VOC concentrations were highest were determined and used to adjust the depths of the dialysis membrane diffusion samplers and the low-flow pump intakes in the March 2001 sampling.

The same nine wells sampled in March 2000 were resampled in March 2001 using all three sampling techniques. The TCE results obtained in the second sampling show better agreement among techniques than those obtained in the first sampling (Table 1 and Figure 2). Once again, the results for cisDCE and VC were similar to those shown for TCE. The change in the depths at which the diffusion samplers and the low-flow pump intakes were positioned made a difference for well 07BR, where the results agreed exactly, and for well 40BR, where the results were much closer than they were during the first sampling in March 2000 (within a factor of 2 or better for TCE and cisDCE).

A tenth well, 02BR, also was sampled in March 2001. This well was not included in the overall analysis of the data because it had not been sampled twice and because the results obtained from this well were unique. According to previous hybrid-purging results, TCE concentrations in this well were on the order of 100 to 200 µg/L, cisDCE concentrations were 30 to 50 µg/L, and VC concentrations were 8 to 11 µg/L; however, no VOCs were detected in samples collected from this well with the polyethylene diffusion sampler in



**FIGURE 1. Logarithm of the concentration of trichloroethene (TCE) recovered by using each of the three sampling techniques in the nine wells sampled in March 2000.**



**FIGURE 2. Logarithm of the concentration of trichloroethene (TCE) recovered by using each of the three sampling techniques in the 10 wells sampled in March 2001.**

**TABLE 1. Constituent concentrations obtained with three sampling techniques.**

[TCE, trichloroethene; cisDCE, cis-1,2-dichloroethene; VC, vinyl chloride; Ca, calcium, dissolved; Fe, iron, dissolved; Cl, chloride, dissolved; Alk, alkalinity, dissolved; mg/L, milligrams per liter; µg/L, micrograms per liter; <, less than; D, dialysis membrane diffusion sampler; L, low-flow purging technique; H, hybrid purging technique; NA, not analyzed; DUP, duplicate; TBLK, trip blank; WBLK, equipment wash blank]

WELL NAME	SAMPLING DATE	SAMPLING TECHNIQUE	TCE (mg/L)	cisDCE (mg/L)	VC (mg/L)	Ca (mg/L)	Fe (mg/L)	Cl (mg/L)	Alk (mg/L as CaCO <sub>3</sub> )
03BR	3/27/00	D	<1	<1	<1	25	280	6	85
		L	<1	<1	<1	26	44	6	85
		H	<1	<1	<1	28	21	6	90
	3/15/01	D	<1	<1	<1	27	<21	NA	76
		L	<1	<1	<1	26	<21	NA	88
		H	<1	<1	<1	25	<21	NA	87
06BR	3/27/00	D	<1	<1	<1	34	397	10	120
		L	<1	<1	<1	38	96	10	120
		H	<1	<1	<1	36	173	9	120
	3/15/01	D	<1	<1	<1	34	<21	NA	110
		L	<1	<1	<1	36	<21	NA	120
		H	<1	<1	<1	34	<21	NA	120
07BR	3/29/00	D	3,100	13,000	1,800	68	2,850	33	69
		L	24,000	39,000	7,200	191	5,390	38	200
		H	16,000	45,000	8,600	184	5,740	42	200
	3/22/01	D	20,000	21,000	3,500	194	7,350	NA	210
		L	20,000	22,000	3,700	168	6,300	NA	200
		H	20,000	20,000	2,800	211	6,450	NA	210
09BR	3/28/00	D	15	3	<1	58	87	17	200
		L	18	4	<1	59	666	18	205
		H	10	2	<1	47	195	12	180
	3/19/01	D	5	4	<1	60	82	NA	190
		L	5	4	<1	52	<21	NA	200
		H	5	2	<1	46	85	NA	190
11BR	3/28/00	D	4	9	<1	14	16	10	50
		L	4	5	<1	12	47	10	30
		H	5	17	<1	16	20	10	50
	3/20/01	D	4	16	<1	17	<20	NA	49
		L	4	10	<1	16	<20	NA	48
		H	5	16	<1	18	<20	NA	45
30BR	3/28/00	D	20,000	28,000	1,600	89	2,800	NA	NA
		L	30,000	23,000	1,300	38	7,750	50	145
		H	34,000	43,000	2,700	113	1,800	51	190
	3/22/01	D	28,000	40,000	3,500	123	848	NA	180
		L	45,000	34,000	2,600	84	6,150	NA	170
		H	28,000	25,000	1,600	81	3,040	NA	150
34BR	3/28/00	D	<1	<1	<1	39	671	14	85
		L	<1	<1	<1	31	547	12	65
		H	<1	<1	<1	41	211	13	90
	3/15/01	D	<1	<1	<1	44	<21	NA	81
		L	<1	<1	<1	43	35	NA	88
		H	<1	<1	<1	44	27	NA	89
38BR	3/29/00	D	29,000	3,800	120	31	1,770	21	151
		L	33,000	4,800	190	30	627	24	146
		H	33,000	5,000	150	31	834	22	149
	3/22/01	D	42,000	4,100	310	54	1,070	NA	150
		L	33,000	4,600	280	47	801	NA	160
		H	33,000	4,400	330	47	530	NA	140

**TABLE 1. Constituent concentrations obtained with three sampling techniques (continued).**

WELL NAME	SAMPLING DATE	SAMPLING TECHNIQUE	TCE (mg/L)	cisDCE (mg/L)	VC (mg/L)	Ca (mg/L)	Fe (mg/L)	Cl (mg/L)	Alk (mg/L as CaCO <sub>3</sub> )
40BR	3/29/00	D	2	39	<1	8	102	2	20
		D-DUP	2	33	<1	8	124	2	32
		L	1	30	<1	8	133	2	45
		H	72	150	<1	20	1,000	8	85
	3/20/01	D	18	87	<1	9	52	NA	29
		D-DUP	18	68	<1	9	<20	NA	28
		L	21	67	<1	8	136	NA	28
		L-DUP	21	74	<1	9	130	NA	28
		H	37	93	<1	14	279	NA	48
02BR	3/20/01	D	<1	<1	<1	50	20	NA	110
		L	8	2	<1	46	308	NA	110
		H	140	51	12	28	1,190	NA	120
TBLK	3/30/00	D	<1	<1	<1	<1	16	2	2
	3/22/01	D	<1	<1	<1	<1	<20	NA	<2
WBLK	4/4/00	L & H	<1	<1	<1	<1	9	<1	<1
	3/21/01	L & H	<1	<1	<1	1	<21	NA	<2

the preliminary sampling conducted prior to the March 2001 sampling. Results obtained with the dialysis membrane diffusion sampler deployed in March 2001 confirmed this finding; all concentrations of TCE, cisDCE, and VC were less than 1 µg/L. When the well was pumped with the low-flow purging technique, however, the TCE concentration was 8 µg/L, and when the well was pumped at a higher rate with the hybrid purging technique, the TCE concentration was 140 µg/L. Similarly, the concentration of cisDCE was 2 µg/L with the low-flow technique and 51 µg/L with the hybrid purging technique. It is possible that VOCs are entering this well through very small fractures that are not visible on the caliper log and conduct contaminated water only when the well is under pumping stress.

**Inorganic Constituents.** Concentrations of dissolved calcium in water collected with all three sampling techniques were similar for six of nine wells sampled in March 2000 (Table 1). In three wells (07BR, 40BR, and 30BR), however, either the dialysis membrane sampler or low-flow purging yielded much lower concentrations than the hybrid purging technique. After the depths of the diffusion sampler and low-flow pump intake were adjusted for the second round of sampling in March 2001, all calcium concentrations differed by an average of only +/- 6 percent for all three sampling techniques in these same nine wells.

Dissolved iron is the most variable parameter measured. The iron concentrations recovered with the diffusion sampler and the low-flow purging technique agreed with the hybrid purging results within a factor of 2 in only two and three of the nine wells sampled in March 2000, respectively (Table 1). Adjusting the depths of the diffusion samplers and the low-flow pump intakes improved this agreement so that iron concentrations recovered with the dialysis sampler and the low-flow purging method agreed closely in five and six of the same nine wells sampled in March 2001, respectively. These results did not vary in any consistent way. Both the diffusion sampler and low-flow purging results were higher than and lower than the hybrid-purging results in different wells. The diffusion-sampler trip blank and pump wash blanks contained very low to less than



detectable concentrations of iron (Table 1); therefore, the variability in iron concentrations does not appear to be the result of cross-contamination between wells or of leaching from the materials from which the samplers are constructed. It is possible that the three sampling methods result in different iron concentrations simply because redox conditions in the bedrock fractures are different from those in the open interval of the borehole. Water collected with different sampling techniques may be exposed to iron with different solubilities.

Samples for chloride analysis were collected during both sampling events, but because of analytical problems chloride data are available only for the March 2000 sampling. Concentrations of chloride agreed well (an average difference of only +/- 5 percent) among all three sampling techniques in all of the nine wells sampled (Table 1). It is likely that these results, like the results for calcium, would agree even more closely if samples were collected at the adjusted depths of the diffusion samplers and the low-flow pump intakes.

Alkalinity data agreed well for seven of the nine wells sampled in March 2000 (Table 1). Like the results for calcium and TCE, results for the diffusion sampler or the low-flow purging method were low in samples from wells 07BR and 40BR. When the depth of the diffusion sampler was adjusted to correspond to the depth of the main contributing fracture in each well, however, alkalinity concentrations obtained with all sampling methods agreed much more closely (within an average of +/- 4 percent).

Alkalinity concentrations in well 02BR agreed very well among the three sampling techniques (Table 1). For calcium, however, concentrations in samples obtained by using both the diffusion sampler and low-flow purging were higher than those obtained by using the hybrid purging technique. Apparently, the diffusion sampler and the low-flow purging pump were positioned at the depth of a fracture that contained water with higher calcium concentrations than most of the other fractures intersecting the open interval of this well. The hybrid purging technique may yield lower calcium concentrations for this well because it results in collection of a sample that is integrated over the whole open interval, and may draw water containing lower calcium concentrations from more fractures at different depths.

Iron concentrations in well 02BR varied in a similar manner to the TCE concentrations. The iron concentration determined in the dialysis membrane diffusion sampler was near detection (20 µg/L), whereas the concentration in the low-flow purging sample (310 µg/L) was an order of magnitude lower than that in the hybrid-purging sample (1,190 µg/L). Again, it is possible that water containing high iron concentrations only enters the open interval of this well when the well is pumped.

**Statistical Comparison.** Data from the nine wells sampled during each of the two sampling events were included in an overall nonparametric analysis of variance on ranks. The results indicate no significant difference (at the 95-percent confidence level) among sampling techniques for VOCs, calcium, iron, chloride, and alkalinity (Table 2). These results remained the same even when the three wells in which VOC concentrations were less than the detection limit were excluded from the statistical comparison.

**TABLE 2. Results of statistical comparison.**

[NSD=No significant difference at the 95-percent confidence interval]

Constituent	Number of observations	Nonparametric analysis of variance (p=0.05)	Tukey multiple comparison test (p=0.05)
TCE	18	NSD	NSD
cisDCE	18	NSD	NSD
VC	18	NSD	NSD
Calcium	18	NSD	NSD
Iron	18	NSD	NSD
Chloride	9	NSD	NSD
Alkalinity	18	NSD	NSD

These results indicate that dialysis membrane diffusion samplers, low-flow purging, and hybrid-flow purging can all be used successfully to collect ground-water samples for analysis for both VOCs and the selected inorganic constituents studied. For both the diffusion sampler and the low-flow purging technique, however, the depth of the fracture contributing most of the contaminated water to the open interval of the well must be known. This conclusion is supported by the fact that the results obtained with the three sampling techniques agreed more closely when the depths of the diffusion sampler and the low-flow-purge pump intake were adjusted to match the depth of the main contributing fracture.

These results also show that caliper logging alone may not be sufficient to identify the location of small fractures that may be important geochemically. The size of a fracture does not necessarily indicate the presence of contaminated water; that is, large fractures do not necessarily produce the water containing the highest concentration of contaminants. Water-quality results obtained using low-flow purging in fractured-bedrock wells at an arbitrary depth, such as the mid-depth of the open interval, may be difficult to interpret. The mid-depth of an open interval has only a small chance of coinciding exactly with the depth of a fracture providing water to the well, and an even smaller chance of coinciding with the depth of the fracture that is contributing most of the contaminated water to the well. This observation has been made at other fractured-bedrock sites (Shapiro, 2002).

The results from well 02BR show that samples collected with diffusion samplers are representative of the water passing through the well's open interval at the specific depth at which it is set under static or steady-state pumping conditions. None of the samples collected with the diffusion samplers placed in this well (dialysis membrane or polyethylene) showed detectable VOC concentrations. Therefore, the ground water passing through this open interval under the flow conditions present in March 2001 was uncontaminated. When the well was pumped with either the low-flow or hybrid purging technique, however, water was drawn into the well from the surrounding fractures that contained VOC-contaminated water. This result implies that the fracture that contains the most contaminated water may be small and may conduct water only when the well is pumped. Thus, the ambient water in well 02BR may be uncontaminated but may become contaminated whenever the well is pumped for sampling.

## **CONCLUSIONS**

On the basis of the study results, all three sampling techniques tested-the dialysis membrane diffusion sampler, low-flow purging, and hybrid high-flow/low-flow purging-appear to recover both VOCs and selected inorganic water-quality constituents equally well. Diffusion samplers and low-flow purging can yield valid results in fractured-rock wells as long as the depth of the main fracture contributing contaminated water to the open interval of the well is known and the intakes of these samplers are positioned at this depth.

Monitoring costs associated with use of dialysis membrane diffusion samplers may be lower than those associated with the purging sampling techniques studied because of the reduction in manpower needs and in time needed in the field for sampling, and because equipment-decontamination and purge-water treatment/disposal costs are eliminated. Dialysis membrane diffusion samplers, although slightly more expensive than currently available polyethylene diffusion samplers, have the added capability of collecting samples to be analyzed for inorganic compounds.

## **ACKNOWLEDGEMENTS**

Funding was provided by the U.S. Navy, Engineering Field Activities-Northeast, Lester, Pa. Sampling and analysis was done by EA Engineering Science and Technology, Iselin, N.J.

## **REFERENCES**

- Giles, G. and Story, J. 1997. "The low-down on low flow." Site Remediation News. 9(3):3-5.
- International Technology Corporation. 1994. "Remedial Investigation Report, Installation Restoration Program, Naval Air Warfare Center, Trenton, New Jersey." International Technology Corp., Edison, N.J., 100 p.
- Lacombe, P.J. 2000. "Hydrogeologic framework, water levels, and trichloroethylene contamination, Naval Air Warfare Center, West Trenton, New Jersey, 1993-97." U.S. Geological Survey Water-Resources Investigations Report 98-4167. 139 p.
- New Jersey Department of Environmental Protection. 1992. "Field sampling procedures manual." Trenton, N.J. 360 p.
- Puls, R.W. and Barcelona, M.J. 1996. Ground water issue: Low-flow (minimal drawdown) ground-water sampling procedures. U.S. Environmental Protection Agency Report EPA/540/S-95/504. R.S. Kerr Environmental Research Center, Ada, Ok.
- SAS Institute Inc. 1989. "SAS/STAT user's guide, version 6, fourth edition, volume 2." Cary, N.C. 846 p.
- Shapiro, A.M. 2002. "Cautions and suggestions for geochemical sampling in fractured rock." Ground Water Monitoring and Remediation. 22(2)150-160.

U.S. Environmental Protection Agency. 1990. "Test methods for analysis of solid waste and waste water: Physical/chemical methods, SW846." EPA/600/R-95-131. 400 p.

Vroblesky, D.A. 2001a. "User's guide for polyethylene-based passive diffusion bag samplers to obtain volatile organic compound concentrations in wells, Part 1: Deployment, recovery, data interpretation, and quality control and assurance." U.S. Geological Survey Water-Resources Investigations Report 01-4060. 18 p.

Vroblesky, D.A. 2001b. "User's guide for polyethylene-based passive diffusion bag samplers to obtain volatile organic compound concentrations in wells, Part 2: Field tests." U.S. Geological Survey Water-Resources Investigations Report 01-4061. 80 p.